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Abstract
The first rainy season in South China (SC) is a concentrated precipitation season, however, it is unclear that in such concentrated precipitation season, characteristics of heavy precipitation concentration degree in SC during the past 50 years. Based on daily precipitation observation data of 192 stations in SC during the first rainy season (April-June) for 1965-2016, the study investigated and analyzed the temporal and spatial variations of the heavy precipitation concentration index (Q index for short). Results showed that the intensity of heavy precipitation over most regions of SC exhibited an increasing trend. The multi-year mean Q index of the heavy precipitation at different stations varied between 0.3 and 0.6, with an average value of 0.375. The heavy precipitation has a concentration trend in the SC inland and western mountain areas and a dispersion trend in the SC coastal area. Notably, both heavy precipitation and the Q index in most inland and western mountain areas showed an increasing trend, denoting a higher flooding risk there. On the other hand, for the duration of heavy precipitation, the 2-day duration of heavy rainfalls had an increasing trend in inland, western Mountain and East Guangdong. The 3-day duration of rainfalls tended to increase steadily in coastal areas and East Guangzhou, and the 4-day duration of rainfalls increased only in the coastal region. In conclusion, the shorter duration heavy precipitation decreased, while the longer ones increased especially in the coast and East Guangdong, which can contribute to the decrease in the Q index but can not denote a decrease in flooding risks. The possible cause may be attributed to the long-duration heavy rainfall that happened in the West Mountain, East Guangdong and Southeast Coast. On the other hand, the frequency and intensity of ongoing heavy precipitation events in coastal cities of South China have increased significantly.

Keywords The first rainy season in South China, Precipitation concentration, Wet periods, Rainfall duration.
1 Introduction

The IPCC Fifth Assessment Report noted that the increase in the frequency and intensity of extreme precipitation events, which causes flood disasters, is a global trend. Many scholars have paid more attention to this field and achieved considerable progress. Westra et al. reported that the amount, intensity, and frequency of heavy precipitation events exhibited positive trends in most areas around the world. For the last 60 years in Europe, some countries have experienced longer and heavier rainstorms. In the United States, the total precipitation has increased by 10%, and extreme heavy precipitation events have increased in recent years (Karl et al., 1998). Also, climate extremes in China have been investigated by many researchers based on different data sets. The results showed that changes in extreme precipitation in China were generally more complicated in the spatial pattern. In the past 45 years, extreme heavy precipitation, precipitation intensity, and rainy days have shown a significantly increasing trend in the middle and lower reaches of the Yangtze River, while the total precipitation has increased sharply in West China. Furthermore, not only the amount of heavy rainstorms has increased, but also the average precipitation intensity has generally tended to increase.

South China (SC) is one of the most serious regions affected by flooding in China. The precipitation in SC during the first rainy season (April-June) is heavy and concentrated with long duration and numerous rainstorm processes, which easily cause flood disasters. In SC, nearly 50% of rainstorms were concentrated in the first rainy season. Serious floods had more than a one-fold increase during the pre-flood season in 1965, 1973, 1978, 1993, 1998, 2001, 2005, 2008, and 2012, especially in 2008 with precipitation increased by 198.2%. The amount of rainfall and frequency of heavy rainstorms showed a slightly decreasing trend during the pre-flood season of SC. Interdecadal change of heavy rainfall in SC was also complex. The extreme heavy precipitation was less than normal from 1977 to 1997 but more than normal from 1977 to 2010 during the first rainy season in most parts of SC. The precipitation presented a significant deficit in the 1980s and abundant in the 1990s in northern SC, respectively. Zhang and Wei proposed that the extreme precipitation (≥ 80 mm) decreased since 1992, and the extreme precipitation has had significant spatial and temporal variation during the pre-flood season in SC in recent years.

Since the severity of heavy rainfall in SC is often related to concentration and duration, it is very necessary to define an index to measure the concentration. Previous several precipitation-related indices, including the annual total precipitation amount, the annual total rainy days, the annual average wet-day precipitation intensity, and the percentage anomaly (Pa) or probability distribution (Pd) were widely used to investigate the rainfall changing pattern or rainfall anomaly grades. The standardized precipitation index (SPI) was also used to assess the spatial-temporal variation of dryness/wetness in the different regions. However, these indices cannot describe the change in precipitation concentration. Recently, some studies used the precipitation concentration index (CI) to analyze the changes in precipitation structure in Algeria and Russia. Based on the concept of information entropy, Li et al. established the index of precipitation concentration to analyze the summer precipitation in China. For SC during the first rainy season, a concentrated precipitation season, temporal and spatial variations of precipitation concentration during the past 50 years remained unclear.
On the other hand, according to the calculation analysis, there was a slight increase in total precipitation and rainstorm days, while a decrease in rainy days during the pre-flood season in SC over the past 52 years. That is, the precipitation intensity and concentration likely increased in SC. However, it is unclear which kind of spatial-temporal variation contributed to the precipitation concentration during the pre-flood season in SC.

Therefore, this study will grasp the structural characteristics and variations of the heavy precipitation in SC during the pre-flood season of the past 50 years by analyzing the $Q$ index of precipitation concentration, which can help to provide a scientific basis for disaster preparedness and mitigation.

### 2 Data and Methods

#### 2.1 Data

The daily precipitation data from 1965 to 2016 was provided by the National Meteorological Information Center with observation data from 192 meteorological stations in SC’s Guangdong, Hainan Province, and Guangxi Zhuang Autonomous Region (GZAR). All data were collected with quality control measures in place. The period from April 1 to June 30 was regarded as the first rainy or pre-flood season of SC and combined with the climatic average from 1965 to 2016.

#### 2.1 Methods

Widely used in physics, the concept of entropy can be used to measure unpredictable information and represent the method of information transmission. Generally, the higher the probability of such information, the wider it spreads and the more times it is used. When the uncertainty of a variable increases, its entropy increases, and the amount of information required to recognize the variable is greater. As precipitation is a skewed distribution, conventional statistical methods are not suitable, while the entropy concept can take direct action on it. Therefore, the concept of information entropy was introduced. The $Q$ index of daily precipitation relative to the total precipitation is used to represent the precipitation concentration degree.

The 38 mm daily precipitation, which is usually located at 95% in the pre-flood season over SC, is regarded as the criterion of heavy precipitation. Considering ≥38 mm as a heavy rain day, persistent rainy days were defined as the rainy period. The $Q$ index defined by Li et al. 8 is used to analyze the structural characteristics of heavy precipitation (≥38 mm) from another viewpoint. The $Q$ index equation of single-station precipitation concentration degree represents the time distribution characteristics as follows:

\[
Q = 1 + \sum_{i=1}^{N} \frac{1}{\ln N} \left[ P(x_i) \cdot \ln P(x_i) \right]
\]

where $P(x_i)$ is the contribution rate of the daily heavy precipitation to the total amount during the pre-flood season, namely

\[
P(x_i) = \frac{R_i}{R}
\]

where $R_i$ is the daily precipitation greater than or equal to 38 mm, $R$ is the total precipitation during the pre-flood season, $i$ is the number of days, and $N=91$ is the total number of days from...
April to June.

In equation (2), $P(x_i) = 0$ indicates that the heavy precipitation on an $i$th day has no contribution to the total precipitation, while $P(x_i) = 1$ means that the heavy precipitation on an $i$th day contributed to the total amount. $P(x_1) = P(x_2) = \ldots = P(x_i) = 1/i$ indicates that the daily precipitation was the same contribution to the total precipitation during the pre-flood season, whose probability of such a situation is impossible in reality. $Q_i = 1$ indicates that the total precipitation is concentrated on a given day, while $Q_i = 0$ indicates that the precipitation is evenly distributed during the pre-flood season. When the $Q$ value is close to 0 (1), this indicates that the precipitation is distributed to more (less) rainy days. If the total precipitation is larger (smaller), the $Q$ value indicates wetter (drier) days. Meanwhile, the Kendall tau rank distance 24 was used to evaluate the significance level of different precipitation parameters’ linear trends.

3 Climatology of the heavy precipitation concentration in the first rainy season over SC

The precipitation during the pre-flood season accounted for 40% to 50% of the annual precipitation in SC, indicating that the pre-flood season was the major flood period and the frequent period of persistent rainstorms with wide-range flood disasters in SC. Over the past 52 years, the heavy precipitation belt showed a southeast-northwest direction and $\geq 400$ mm accumulated precipitation concentrated in northern Guangxi and most parts of Guangdong during the pre-flood season of SC (Fig. 1a). The precipitation in the Southeast Coast was more than 500 mm with an increasing linear trend. In addition, the heavy precipitation exhibited an increasing trend in the northern part of Guangxi, eastern Guangdong, and along the Southeast Coast (Fig. 1b). In other words, the precipitation might be heavier in the concentrated areas of heavy precipitation.
Fig. 1 Total heavy precipitation spatial distribution (unit: mm) (a) and their linear trend (mm/10a) (b) in the first rainy season in SC during 1965-2016. The trends with the cross are significant at the level of $p < 0.1$.

On the other hand, Fig. 2 shows the multi-year mean climatological $Q$ index spatial distribution and its trend during the pre-flood season in SC from 1965 to 2016. The multi-year mean $Q$ index at different stations varied between 0.3 and 0.6 with an average value of 0.375, indicating that the precipitation was more dispersive (more rainy days), compared with the counterpart of Northwest China summer precipitation with a $Q$ index of more than 0.6. Specifically, the $Q$ index changed from 0.3 to 0.375 over Guangdong inland and eastern Guangxi. The value varied from 0.375 to 0.6 in the coastal region, western Guangxi, and most parts of Hainan Province, which means the heavy rainstorm was easily concentrated in the coastal area rather than the inland. The outcome was consistent with the research of Peng et al. 33 However, the inland $Q$ index presented an increasing trend, meaning that the heavy precipitation increased and showed a centralized trend and more rainfall occurred on a less rainy day with increasing intensity. Meanwhile, the $Q$ index of eastern Guangdong, Hainan Province, and the southwest coastal area showed a decreasing trend, that is, the precipitation showed a dispersion trend in the coastal area. Therefore, the precipitation structure was much different between the coastal and inland areas during the pre-flood season in SC. Therefore, four areas were chosen according to the $Q$ index value and trend, including the western mountain area, the coastal area (Hainan Province, the coast of Guangdong and Guangxi), the inland area (the eastern part of Guangxi, and the western part of Guangdong Province), and the eastern Guangdong (Fig. 2a, Table 1). The precipitation structural characteristics in various areas were further detailed as follows.
Fig. 2 The climatological spatial distributions of precipitation concentration degree Q index (a) and their trend (0.0001/10a) (b) in the first rainy season in SC during 1965-2016. The trends with cross signs are significant at the level of $p < 0.1$.

4 Temporal changes in concentration property of heavy precipitation

In the past 52 years, the total heavy precipitation and $Q$ index showed a decreasing trend in eastern Guangdong (Fig. 3a) and the coastal area (above the 95% confidence level) (Fig. 3b), that is, the rainy days increased and the precipitation intensity decreased. However, it should be noted that the total precipitation and $Q$ index showed an increasing trend in the inland over SC (Fig. 3c). The inland precipitation concentration showed a centralized trend with the total precipitation
increasing during the pre-flood season, indicating more heavy rainfall occurred in fewer rainy days, that is, the precipitation intensity increased, and more local floods were prone to occur in SC’s inland.

Although the total heavy precipitation in the western mountain of SC slightly decreased during the pre-flood season over the past 52 years, the Q index showed a significantly increasing trend (above the 95% confidence test) (Fig. 3d). The total precipitation slightly decreased with rainy days significantly decreasing, thus the precipitation intensity increased.

Table 1 gives the characteristics summarization of different four regions. The results showed the rainy days increased and the precipitation intensity decreased in eastern Guangdong and the coast, while the rainy days decreased and the precipitation intensity increased in inland and western mountain areas.

![Fig.3 The time series of the regional heavy precipitation (blue bar) and the Q index (red line) as well as their linear trend(black line) in the first rainy season for 1965-2016a over SC: (a) eastern Guangdong, (b) coastal area, (c) SC’s inland, (d) western mountain.](image)

<table>
<thead>
<tr>
<th>Region</th>
<th>SC inland</th>
<th>Western mountain area</th>
<th>Eastern Guangdong</th>
<th>Coastal area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station numbers</td>
<td>33</td>
<td>37</td>
<td>30</td>
<td>74</td>
</tr>
<tr>
<td>Q index</td>
<td>&lt;0.375</td>
<td>&gt;0.375</td>
<td>&lt;0.375</td>
<td>&gt;0.375</td>
</tr>
<tr>
<td>Q trend</td>
<td>+</td>
<td>+(significant)</td>
<td>–</td>
<td>– (significant)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
5 Changes in heavy precipitation duration in different regions

Some scholars have studied the heavy precipitation based on the persistent rainstorm characteristics during the pre-flood season in SC 31 and changes in the extreme values of rainstorms in the southeast coastal area 30, but few scholars pay close attention to the changes in the structure of heavy precipitation during the pre-flood season in SC. The above analysis shows that the heavy precipitation was different among four regions during the pre-flood season in SC. Therefore, in the following, the duration and variation trend of precipitation in the four different regions were analyzed.

In the past 52 years, single-day heavy precipitation was the main character during the pre-flood season in inland SC. The probability of a one-day rainy period was 75.6% with a contribution rate of about 87.0% to the total rainy days. Over the past 52 years, the rainy period of one to two days was dominant with a contribution rate of 95.0% to the total rainy days (Fig. 4a). Further analysis showed that the one-day rainy period was dominant before the 1990s. Persistent precipitation of more than three days frequently occurred from the early 1980s to the end of the 1990s. Some research found, that in the context of global warming, precipitation in SC experienced a phase transition from a deficiency regime to an abundance regime in the early 1990s 32. In consequence, the one-day rainy period became less, there had been more persistent heavy rainfall. After the 2000s, the persistent precipitation gradually decreased from four days to two days, while those of five days mainly occurred in the early 1980s and the early 1990s (Fig. 4b). Thus, both the one-day and three-day precipitation decreased over the past 52 years (the former above the 90% confidence test). However, the two-day counterpart showed a significantly increasing trend in recent years (below the significance test) (Fig. 4c).

<table>
<thead>
<tr>
<th>trend</th>
<th>Precipitation intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

The probability of a one-day rainy period was 82.9% in the western mountain area with a
91.2% contribution rate to the total rainy days. Similar to the inland SC, the rainy period of one to two days was dominant over the past 56 years with a contribution rate of more than 96.0% to the total rainy days, but the rainy period of three or more days only accounted for about 4.0% (Fig. 5a). The interannual and interdecadal variation characteristics of the rainy period were significant, which were dominated by one-day heavy precipitation from the early 1970s to the early 1980s, followed by four-day heavy precipitation in the mid-1990s, and then annually decreased to two-day precipitation (Fig. 5b). From the variation trend of the rainy period in different duration, the one-day rainy period and three days or more showed a decreasing trend (the former above the significant level), while the two-day rainy period significantly increased. (Fig. 5c).

Fig. 5 is the same as Fig. 4 but for the western mountain area in SC

The one-day rainy period probability was 69.6% in eastern Guangdong with an 83.6% contribution rate to the total rainy days, and the contribution rate of the one-day and two-day periods of heavy rain was about 92.0% to the total rainy days, indicating that the shortest period of heavy rain was still dominant. However, compared to the western mountain and inland areas of SC, the persistent precipitation of three days or more increased to about 8.0%, that is, the probability of persistent heavy precipitation in eastern Guangdong was slightly higher than in the inland and mountain areas. However, its temporal distribution showed significant interannual changes, dominated by heavy precipitation lasting two or more days in the mid-1970s and early 21st century, and the one-day heavy precipitation appeared from the late 1970s to the early 21st century (Fig. 6b). The different rainy duration variation trend presents the different characteristics. The rainy period of one, four, and five or more days slightly decreased, while the two-day and three-day rainy periods increased (Fig. 6c).
It should be noted that, like in eastern Guangdong, the probability of one-day heavy precipitation was 70.1% with a contribution rate of 84.0% to the total rainy days in the coastal area of SC in the pre-flood season. Similarly, the contribution rate of the one-day and two-day rainy periods to the total rainy days was about 92.0% with three or more counterparts at 8.0%. Therefore, the probability of persistent heavy precipitation in the coastal area and eastern Guangdong was relatively larger compared with those in the Western Mountain and inland areas of SC. Their spatial-temporal distribution showed significant interannual and interdecadal variation. Before the mid-1980s, the one-day and two-day periods of heavy rain had a positive contribution, and the duration lasting more than three days had significantly increased since the mid-1980s (Fig. 7b). The variation trend of persistent precipitation duration (Fig. 7c) showed that the one-day to two-day periods of heavy rain decreased while the heavy rain of three or more days increased, indicating that persistence heavy precipitation has increased from 1965 to 2016 in the coastal area of SC, which is consistent with the research results of Peng 33.

In summary, the heavy precipitation in the four different regions of SC showed different spatial-temporal characteristics. Both one-day and two-day precipitation dominated all four regions, but the former showed a decreasing trend. The two-day heavy precipitation showed an increasing trend in the inland and western mountain areas as well as eastern Guangdong. The
three-day counterpart showed an increasing trend in the coastal areas and eastern Guangdong. Furthermore, the equivalent of four or more days showed an increasing trend in the coastal area.

<table>
<thead>
<tr>
<th>Region</th>
<th>SC inland</th>
<th>Western mountain area</th>
<th>Eastern Guangdong</th>
<th>Coastal area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain spell</td>
<td>Probability</td>
<td>From the early 1970s to the early 1980s</td>
<td>From the late 1970s to the early 2000s</td>
<td>Before the mid-1980s</td>
</tr>
<tr>
<td>1 Day</td>
<td>Concentrated period occurred</td>
<td>Significant decrease</td>
<td>Significant decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td></td>
<td>Probability</td>
<td>75.6 %</td>
<td>82.9 %</td>
<td>69.6%</td>
</tr>
<tr>
<td>2 Days</td>
<td>Concentrated period occurred</td>
<td>Before the 1990s</td>
<td>After 2004</td>
<td>After 2004</td>
</tr>
<tr>
<td></td>
<td>Trend</td>
<td>Increase</td>
<td>Significant increase</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Probability</td>
<td>19.7%</td>
<td>13.9%</td>
<td>22.2%</td>
</tr>
<tr>
<td>3 Days</td>
<td>Concentrated period occurred</td>
<td>From the early 1980s to the late 1990s</td>
<td>The early 2000s</td>
<td>From the mid and early 1970s to the early 2000s</td>
</tr>
<tr>
<td></td>
<td>Trend</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Probability</td>
<td>3.9%</td>
<td>2.5%</td>
<td>6.1%</td>
</tr>
<tr>
<td>4 Days</td>
<td>Concentrated period occurred</td>
<td>Around the 1980s and 2000s</td>
<td>Beginning in the mid-1990s</td>
<td>From the mid and early 1970s to the early 2000s</td>
</tr>
<tr>
<td></td>
<td>Trend</td>
<td>Increase</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td></td>
<td>Probability</td>
<td>0.6%</td>
<td>0.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>5 Days and above</td>
<td>Concentrated period occurred</td>
<td>The early 1980s and early 1990s</td>
<td>After the late 1960s to the early 2000s</td>
<td>From the mid and early 1970s to the early 2000s</td>
</tr>
<tr>
<td></td>
<td>Trend</td>
<td>No trend</td>
<td>No trend</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

6 Conclusion and discussion
Based on the daily precipitation data of the pre-flood season in SC from 1965 to 2016, the research shows that the heavy precipitation was mainly concentrated in the western mountain area, eastern Guangdong, and the southeast coast, with cumulative precipitation of more than 400 mm and a linear increasing trend. Using the Q index, the changes in the concentration property of temporal heavy precipitation distribution and the possible causes of these changes during the pre-flood season in SC were investigated. The specific conclusions are as follows:

(1) The multi-year mean Q index, representing the concentration of precipitation, in SC, was mainly distributed between 0.3 and 0.6 with an average of 0.375. Heavy rain became more decentralized (concentrated) when the Q index was smaller (bigger) than 0.375 and closer to 0 (1).

(2) Regional difference in heavy precipitation concentration in SC is obvious. The heavy precipitation showed different spatial-temporal characteristics during the pre-flood season among four regions, namely the western mountain area, the coastal area (Hainan, coastal Guangdong, and the coastal Guangxi), and the inland area (eastern Guangxi and western Guangdong), and eastern Guangdong. The heavy precipitation concentration in the pre-flood season was different between the coastal and inland areas in SC. The \( Q \) index of Guangdong inland and eastern Guangxi was from 0.3 to 0.375, while those of the coastal area, western Guangxi, and most parts of Hainan Province were from 0.375 to 0.6, indicating that heavy precipitation tended to concentrate in the coastal area rather than the inland area. However, the linear trends analysis indicates that the heavy precipitation has a concentration trend in the inland and a dispersion trend in the coastal area. Notably, both heavy precipitation and Q-index in most inland and western mountain areas showed an increasing trend, denoting a higher flooding risk there.

(3) Heavy precipitation also showed differences in duration among the four regions. One-day and two-day precipitation dominated over four regions, but the former showed a decreasing trend. The two-day equivalent showed an increasing trend in the inland and western mountain areas as well as eastern Guangdong. The three-day counterpart showed an increasing trend in the coastal areas and eastern Guangdong, and those of four days or more showed an increasing trend in the coastal areas.

The heavy precipitation duration had a transition during the late 1980s to early 1990s in four areas. Pertinent analyses reveal a close relationship between such decadal precipitation shifts and moisture budgets, which are mainly modulated by the meridional component 32. Moisture contributions for the source regions of first rainy season precipitation over South China are impacted by the South China Sea summer monsoon (SCSSM) activities. Before the onset of SCSSM, the moisture associated with climatological precipitation over South China was mainly contributed by the land regions, followed by the ocean regions 33. Furthermore, the snow cover in the preceding winter also can impact the atmospheric circulation, which in turn affects precipitation. In the future, it will be analyzed the causes of the changes in the heavy precipitation structure in South China during the first rainy season, based on such as water vapour transport, circulation characteristics and ocean changes.

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Author contribution Hui Li contributed to manuscript preparation, as well as the preparation of tables and figures. Liang Zhao was responsible for data collection and analysis. Yamin Hu contributed to experimental design and paper submission. ChaoYu focused on literature revision and discussion.

Data availability the homogenized station data in China (http://data.cam.cn)

Declarations

Competing interests the authors declare no competing interests.

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